AN INVESTIGATION OF THE DISTRIBUTION
PATTERN OF FUEL SPRAYS UNDER
CONDITIONS OF INTEREST IN JET ENGINES

A Thesis submitted to the
Faculty of the Graduate School of the
University of Minnesota

By

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In Partial Fullfillment of the Requirements
for the Degree of
Master of Science in Aeronautical Engineering

May 1956

Thesis

ACKNOWLEDGMENTS

I wish to express appreciation to Professor Thomas E. Murphy for his guidance and encouragement, to Lcdr. R. Koch for his assistance and sympathetic ear, to William J. Alden for his assistance in construction of the apparatus, and to the Mechanical Engineering Department for the loan and use of photographic apparatus and facilities.

I wish also to extend heartfelt thanks to my wife for her great understanding, encouragement and assistance throughout the period of my academic studies.

This project was sponsored by the United States Navy, through the United States Naval Postgraduate School program, and used the combined facilities of the Aeronautical and Mechanical engineering Departments of the University of Minnesota.

TABLE OF CONTENTS

SUMMARY

A knowledge of the influence of the many variables upon the distribution patterns of liquid fuel sprayed into air streams is needed as an adjunct to the design of combustors. A possible means of acquiring this knowledge is through the use of experimental apparatus simulating a combustor and the use of photographic methods and techniques for the analysis of the effects of variation in fuel vaporization parameters. A fuel injector mounted in a glass-walled test section of a heated wind tunnel is used herein to simulate the preignition zone of a combustor. A press-type camera with a close-up lens and a high intensity flash unit of a very short pulse duration afforded a photographic method of obtaining fuel spray data.

Preliminary tests with the apparatus revealed very poor temperature and velocity profiles when operating at elevated temperatures and an impingement of the spray upon the test walls shortly after injection. Typical combustor fuel-air ratios were also unattainable.

The use of photographic methods for the investigation of the spray pattern were found feasible but a proposed spread index was found to be of doubtful value because of the difficulties involved in correctly ascertaining the location of the edge of the spray.

Enlargements of photographs enabled comparisons of the effect of the varying of the fuel pressure from 75 to 150 psi, the air

temperatures from 60°F to 300°F, and the air velocities from 0 to 80 fps. All tests were conducted at 27 in. Hg abs, static pressure.

INTRODUCTION

A knowledge of the influence of the many variables upon the vaporization rates and distribution patterns of liquid fuel sprayed into air streams is needed as a necessary adjunct to the rational design of high output combustors for jet engines.

A droplet of a volatile liquid projected into an air stream diminishes in size as it travels because of a loss of molecules from its surface to the surrounding atmosphere. An idealized assumption might be that the droplet vaporizes at a rate such that a stoichiometric mixture is left in its wake. This assumption is not in accord with the facts and is therefore of little value in analyzing the situation. The rate of evaporization is a function of variables[1] such as (1) the airstream velocity, temperature and static pressure, (2) the droplet velocity, initial temperature and diameter, and (3) the physical properties of the fuel and its vapor. If a fuel droplet is traveling behind another, the rate of evaporization of this droplet is affected because of the presence of a fuel vapor already in its path. This fact appreciably increases the difficulty of analyzing the vaporization of fuels when more than one droplet is under consideration, as is the case in a fuel spray. Further complication is introduced when there is an ignition zone downstream of the point of injection because the rate of vaporization is then influenced by the rate at which the spray droplets receive heat energy from

the flames and other hot bodies by radiation[2].

Under conditions found in a jet engine where the fuel is injected continuously into a moving airstream, the fuel leaves the nozzle as a ligament or sheet[3] which almost immediately begins to break up into varied sized droplets. These droplets can be considered to be originally moving at the same velocity and shortly thereafter accelerating or decelerating to the air stream velocity. The smaller droplets lose their mass more readily than the larger droplets and acquire the stream velocity more rapidly. The mass of vapor given off by the droplets is carried along with the air, and is continuously being increased by more vapor from larger, not yet completely evaporated, droplets. The total amount of fuel vapor present at any particular cross section of the air stream consists then of the total vapor given away by all the drops prior to reaching that cross section. The evaporation takes place immediately after the start of injection with the exposing of large areas of liquid surface of the droplets to the atmosphere enabling heat transfer to take place, with the droplets losing mass by evaporation and diffusion into the air. The initial rate of heat transfer is some function of the initial temperature difference between the fuel and the air. The fuel droplets reach their equilibrium or wet bulb temperatures asymptotically with time. This initial heat transfer[4] becomes less efficient the greater the injected fuel quantity, even though the total heat transferred is greater. This is due to the aforementioned intereffect of one drop upon another.

Some work has been done using single droplets for study.

Ingebo[5] made an investigation to determine the vaporization rates of pure liquid drops vaporizing under conditions similar to those occuring in aircraft combustion systems. His method of experimentation was to simulate a drop of liquid with a wetted cork sphere that was placed in an airstream of constant mass-flow rate and varying temperature. Liquid was injected into the sphere at a rate equal to the vaporization rate and the loss of liquid by vaporization from the sphere's surface determined. He also determined the pressure effects upon vaporization rates of pure liquids in gas streams for single constant diameter drops simulated by wetted porous spheres inserted into air streams[6]. El Walkil, et al[3], made theoretical calculations and experimental study of the unsteady-state portion of the total vaporization time of single fuel droplets injected into air.

The rate of vaporization of a cloud of fuel droplets depends upon the mean diameter of the droplets, or the droplet size distribution. In order to make any comparisons or correlations with single drop data, the mean drop concept is necessary. A mean drop diameter is the size of a droplet having the same surface-to-volume ratio as the spray. Data relating vaporization rates of single drops to that of sprays is notably lacking. Ingebo[1] used photographic techniques to obtain the drop size distribution and drop velocity data for iso-octane injected contra-stream from a simple orifice directly into a turbulent air stream. A camera unit was used to obtain photomicrographs of the spray. Motionless images of the high-velocity droplets were obtained on film by means of a rotating mirror and synchronized flash system.

York and Stubbs[7] used photographic methods to determine size distributions of drops in a spray by photographing a small known volume of the spray and counting and measuring the drop images. Double exposures on the same film, separated by a known time interval, enabled calculation of the velocities of the drops.

An alternative to photographic methods of obtaining drop sizes is to take actual physical samples of the fuel, fuel vapor, and air mixtures at various locations downstream from the point of injection to determine the mixing and distribution of the fuel. In this manner, total and liquid fuel-air ratios could be determined throughout the spray area. Longwell and Weiss[8] did some work involving the mixing and distribution of liquids in high velocity air streams using two different experimental techniques, one for measuring the distribution of liquid fuels as droplets and one for measuring fuels which are chiefly gaseous at the measuring station. Both methods involved removal of stream samples through total head probes.

Bahr[9] improved upon this technique in his investigation of the evaporation and spreading of iso-octane sprays over a range of inlet air conditions common in ram-jet engines. At a single air-flow setting and fuel-injection rate, he obtained both the total and liquid fuel distribution across the test section by use of probe samplings. The probe samples were conducted to a heater to ensure complete evaporation and thence to an NACA mixture analizer[10]. He was then able to express the degree of spray evaporation in percent of fuel evaporated by means of an empirical formula utilizing inlet air and fuel injection parameters.

Similarly, the distribution pattern of the spray was expressed in terms of a spread index formula.

The probe sampling technique necessitates an insertion of a foreign object into the fuel spray path with the attendant complication of the effects upon the spray due to its presence. It is this fact that lends an attractiveness to the idea of using a camera mounted external to a glass-walled test section to record spray data.

It is the purpose of the investigation herein to establish the feasibility of extending the use of photographic methods to the investigation of the distribution pattern of the spray and the droplet sizes and dispersion during the initial stages of fuel injection.

A press-type camera equipped with a close-up lens and a mercury arc lamp light source are used to obtain photographs of benzene sprayed into a glass-walled test section of a wind tunnel that is operating at less than atmospheric pressure under controlled air temperatures and velocities.

APPARATUS

Fig. 1 is a schematic diagram of the wind tunnel and air supply system. The tunnel walls are one-eighth inch steel welded together and reinforced with angle iron strips. The air flow is drawn through the tunnel by means of a vacuum created at the air inlet to a centrifugal compressor. The prime mover is a 165 horsepower Lycoming tank engine driving the compressor at a speed ratio of 7.48:1. Fig. 2 and Fig. 3 are photographs of the tunnel, prime mover, and compressor unit.

The air flow path is through a tunnel intake port whose area is controlled by a valve, thence through a heater section into a settling chamber provided with screens to damp large scale turbulence from which the air is accelerated through a nozzle into a test section. The heater section contains twelve Chromalax 230 volt, 2350 watt, fin-strip electric heaters. Fig. 4 and Fig. 5 are schematic drawings of the heater locations and wiring circuit.

The square test section with inside dimensions of four inches and a length of twenty inches has one-half inch thick pyrex glass side walls for visual and photographic observation. The static pressure tap and temperature and velocity probes are located at the entrance to the test section to enable the measurement of temperatures, pressures and velocities of the air prior to the point of injection of fuel. The fuel is injected into the air stream through a Monarch five gallon per hour, thirty degree cone, high-velocity fuel nozzle located on the test section axis at the test section entrance. The fuel system consists of a fuel tank

with a water jacket, a flow-meter, a pressure gage, and necessary control valves and piping. Compressed carbon dioxide gas provides the fuel system pressurization. A one-half inch pipe serves as a mount for the fuel nozzle and as a container for the fuel tubing and the coolant water. The fuel tank is submerged in a tank of water and maintained at water tap temperature.

The fuel-vapor mixture, after leaving the test section, proceeds through a diffuser into a surge tank equipped with safety blow-out valves to relieve the pressure in case of accidental ignition or explosion. From the surge tank, the fuel-vapor air mixture is ducted into a manifold that leads to the compressor inlet.

A bleed valve is located between the surge tank and manifold to provide another control over the degree of vacuum obtained. Water is sprayed into the fuel-vapor and air mixtures at this point to quench the temperatures down to safe limits for compressor operation. From the compressor the mixture is ducted into a large manifold and exhausted to the atmosphere.

The exterior walls of the tunnel settling chamber and nozzle are lagged with two layers of one-half inch fiberglass blanket over which asbestos sheeting is applied in an effort to reduce heat losses through the walls when operating at the higher air temperatures.

A Model C Mercury Arc Lamp Power Supply manufactured by the Huggins Laboratories flashes a GE A H6 mercury arc lamp. The lamp has a pulse length of 10 microseconds and a pulse power of 2.5 watt-second. The power supply provides a high voltage storage condenser that discharges through the lamp to produce the light

pulse, the discharge controlled by a modulated air spark gap in series with the lamp and storage condenser.

A 4" x 5" Speed Graphic camera with a Kodak Ektar f:4.5 lens photographs the spray. The camera equipped with a Tiffen + 3 close-up lens enables close-up photographs of the spray. Fig. 6 shows the test section, the camera mount bracket, and the lamp reflector in position. The thermocouple switches and potentiometer are contained in the box in the lower right hand corner of the photograph.

A shielded thermocouple at the entrance to the test section gives the air stream temperature. The mercury manometer connected to the static pressure tap located at the test section entrance gives the gage static pressure. A total pressure probe located in the same vicinity is connected to an inclined alcohol manometer U-tube that is in turn connected to the static pressure tap to give the dynamic pressure readings for velocity calculations.

Fuel flow is measured by a fuel rotameter and fuel pressure is determined by the CO_2 pressure applied. The fuel temperature is determined by the average readings of two thermocouples, one located in the water of the fuel tank water jacket and the other in the exit pipe carrying off the nozzle probe coolant water.

A thermocouple is installed in the ducting leading to the compressor unit to provide the operator with a means of determining that the temperature limits of the compressor are not exceeded. All thermocouples are wired to a switchboard and a direct reading Leeds and Northrup Potentiometer Unit that measures directly in degrees, Fahrenheit. The potentiometer was set into a box and surrounded by glass wool to protect it from the air currents.

The prime mover and compressor unit are controlled by throttle adjustment at a remote control station panel containing tachometer, cylinder head temperature gage and oil pressure gages.

Fig. 7 shows the CO_2 tank, the fuel rotameter and pressure gage and the manometer board.

EXPERIMENTAL PROCEDURE

A darkened room was essential to the use of an open shutter photographic technique and since the mandatory ventilation of the test cell prohibited the closing off of all outside light sources, all photographic tests were conducted at night. The afternoon prior to a contemplated test run was spent in preparations such as:

(1) Bringing fluid level of benzol reservoir to the full mark.

(2) Starting tap water flowing into the water jacket surrounding the benzol reservoir and adjusting the flow to keep the fuel tank submerged so that the benzol would be at the tap water temperature during the test runs.

(3) Bringing the prime mover fuel and oil supply up to the full level to forestall engine stoppage due to fuel starvation during any test run.

(4) Checking all thermocouple circuits for satisfactory operation.

(5) Ensuring the test section probes and manometer connections were as desired.

(6) Pre-calculating the manometer fluid levels for dynamic pressure required for each temperature and static pressure of operation so as to give the desired test section velocities.

(7) Mounting and adjusting the camera unit and arc lamp unit as desired.

After completion of a pre-start check-off list, and when ready to begin the test, the prime mover was started and brought up to a speed of 1250 RPM. The fuel nozzle coolant water and the desired electric heater switches were turned on. As the heaters came up to temperature, the quenching spray water for the gases entering the compressor was turned on. The heater section, the switches, variac units, and fuel and water plumbing are to be seen in Fig. 8 and Fig. 9.

An interval of fifteen to thirty minutes was required to allow the tunnel to heat up to a desired temperature. During this time the camera was focused and loaded with film, and the arc lamp power supply turned on. The camera bellows were extended to their maximum, giving about twelve to fifteen inches distance from lens to the fuel spray center-line. If close-ups were desired, the close-up lens was attached in front of the camera lens and the camera mounted to give approximately a distance of six inches from the lens to the fuel spray center-line. A velocity probe or wire extended vertically into the test section in the spray center-line was used to focus the camera.

The barometer reading was obtained and a quick calculation was made which indicated the necessary mercury manometer reading

needed to give the desired test section static pressure.

The adjustments necessary to get the test section at a desired pressure, velocity and temperature necessitated many trial and error settings of the prime mover RPM, the heaters in circuit, the tunnel intake throttle, and the air bleed throttle. During this process rapid vertical temperature profiles were obtained with the thermocouple probe. The test point temperature and velocity were determined by positioning the thermocouple and velocity probe at a point that gave the estimated average test section temperatures as obtained from the profiles. An hour was usually required between the time the prime mover was started and the time when a test point was achieved. The fuel valve was then turned on, the fuel pressure adjusted, and the fuel flow rate noted. The camera shutter was cocked, the film holder cover removed and the room lights turned off. The camera shutter was opened, the arc lamp flashed by pressing a button switch on the power supply unit, and the camera shutter closed. The room lights were then turned on, the fuel valve turned off and the film holder reloaded. Preparations for the next picture sequence were then made by the aforementioned trial and error adjustments. The tunnel shut-down procedure was essentially the reverse of the starting process, excepting the tunnel was operated with heaters off at a moderate velocity for a time until the heaters had cooled off.

The photographs were then processed in the darkroom and the negatives examined. Contact prints and enlargements were made to facilitate the examination of the photographic data.

Kodak Royal Pan sheet film with a tungsten exposure index of 160 was used with a camera setting of f:4.5. The development time was made fifty per cent over the normal time using Kodak DK-50 developer.

RESULTS AND DISCUSSION

A considerable number of man-hours were required to adapt the wind tunnel[11] to operate at less than atmospheric pressure and at higher temperatures. The number of heater units was increased to twelve, the test section plate glass was replaced with pyrex glass, the soldered thermocouples and velocity probes replaced by silver soldered units, and much of the test equipment replaced to suit the needs of the proposed tests.

Preliminary dry runs of the equipment for familiarization and study revealed a very poor temperature profile when operating at elevated temperatures. Ambient temperature runs showed flat temperature and velocity profiles but as the operating temperature was increased, the temperature gradient from the lower half to the upper half of the test section became progressively larger. See Fig. 10 and Fig. 11. The heater distribution pattern was thought to be at fault therefore the heaters were re-located from a symmetrical arrangement to the arrangement shown in Fig. 5, where a greater number of heaters were located at the bottom of the heater section. The test section profiles showed only a slight change for the better. Profiles taken at upstream

stations between the heater section and the nozzle to the test section indicated a large loss of heat to the walls and an apparent gradual upward convection of heat as the air traversed the length of the settling chamber. The bottom wall of the tunnel was mounted onto metal stands, perhaps accounting for some large heat conduction away from the lower tunnel walls in spite of attempts at insulation. Time did not permit further attempts at correction as it was apparent some major structural changes might be required. It was decided to proceed with the tests and use the temperature profiles as a basis for applying corrections as needed.

A thirty microsecond pulse "Strobelux" flash unit was used to obtain preliminary photographs. Several positions of the light on either side of the test section were evaluated with the position shown in Fig. 12 being adapted as the most promising. The flash lamp was mounted next to the camera, as close to the test section as cramped quarters allowed, at an incidence to the tunnel glass walls of about sixty degrees. This allowed the reflection of light off of the spray drops to enter into the camera and all other light to pass through the far side glass walls with no reflection. This gave photographs that had white colored drops against dark back-grounds. Unfortunately the "Strobelux" was not of short enough duration to give defined drops, but rather gave long dashes and streaks. Fig. 13 is an example. A mercury arc lamp flash was then tried and gave the gratifying results as shown in Fig. 14. However, a penalty was exacted for its use in that the unit gave considerable trouble

during the course of the experimental tests due to circuits overloading and fuses burning out. The camera depth of field, particularly in the cases where using the close-up lens, was very narrow and necessitated extreme care to insure that the plane of focus was centered at the spray axis.

It was expected that the temperature would have the greater influence upon the vaporization of the benzene fuel spray, making it the logical choice as the major variable.

The static pressure and the air velocity were maintained at some constant value for each series of tests. Several combinations were tried before selecting the conditions that were the most compatible with the operating limits of the apparatus. The first series of photographs were at a static pressure of 27 in. Hg. abs., 80 fps air velocity and a fuel-air ratio of .0175 with the air temperatures varying from 65° F to 300° F. An examination of these photographs revealed a disturbing increase in drop sizes at the high temperatures. This was attributed to the fact that maintenance of constant velocity and pressure with varying temperatures gave varying air mass flow rates which necessitated the varying of the fuel pressure to maintain a constant fuel-air ratio. The droplet size was strongly influenced by the fuel pressure and as a consequence, completely masked any temperature effects. This and the remaining series of tests were therefore conducted at some constant fuel pressure for each series and the effects of the fuel-air ratio changes between each test point assumed as negligable.

Over sixty photographs of the sprays were made for a constant

test section static pressure under conditions of varying fuel pressure, air velocity, and temperatures during the course of the development of photographic technique and the obtaining of photographic data. Table I lists the more satisfactory photographs and the test conditions for which they were obtained. The costs of reproduction necessitated the inclusion of only the more choice photographs and enlargements herein.

The analysis of the photographs was mainly confined to the upper half of the spray cone due to the aforementioned test section temperature profile difficulties. It was then assumed, for the purpose of the analysis, that the spray pattern was symmetric about the injection axis and that the influences of each variable upon the vaporization rate included both the effects upon the atomization process and the effect upon the evaporation process.

Bahr[9] determined local fuel air ratios downstream from a sample orifice injector by obtaining probe samplings of an iso-octane fuel injected contrastream. The distribution pattern was then expressed in terms of a spread index M, where M is the negative reciprocal slope of a straight-line relation between the logarithm of the local fuel air ratio and the square of the radial distance from the spray axis. The relation used was:

$$f = \frac{W_f}{W_a} \frac{R^2}{M} e^{-\frac{r^2}{M}}$$

where f = Local fuel-air ratio at some point in spray

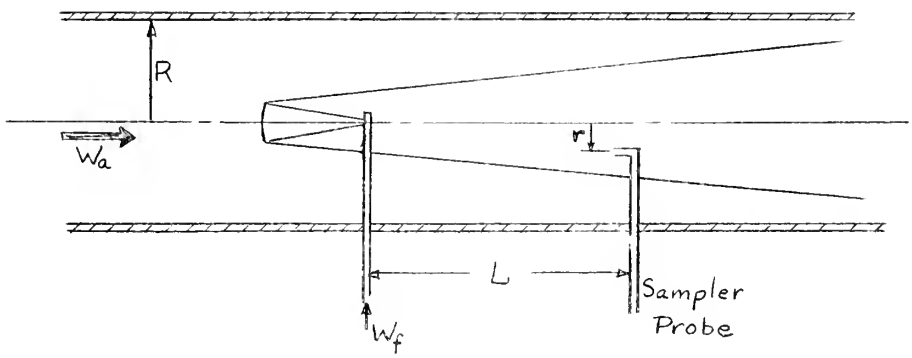
W_f = Fuel flow rate, lb/sec

W_a = Air flow rate, lb/sec

R = Radius of test section duct, ft.

r = Radial distance from a survey point to the axis of injection, ft.

M = Spread index, ft^2.



For iso-octane injected contra-stream.

This author sought to obtain a similar index for benzene sprayed with the air-stream direction by an analysis of the spray geometry as obtained from photographs. It was believed that the cone angle of the spray would vary downstream in a manner dependent upon the fuel pressure and air pressures, velocities, and temperatures and that such variations could be expressed in terms of a spread index.

The photographs obtained were carefully scaled off and radial measurements, r_e, to the apparent fuel spray edge were made at axial distances of one, two, three and four inches downstream of the injector. The fuel spray impinged upon the tunnel walls a short distance downstream of the four inch station, limiting the analysis to the first four inches after injection. Measurements gave a spray cone half-angle of 30.5 degrees just immediately after the point of injection, with a decreasing of the angle with distances downstream. The 30.5 degree angle was projected downstream from the injector and was

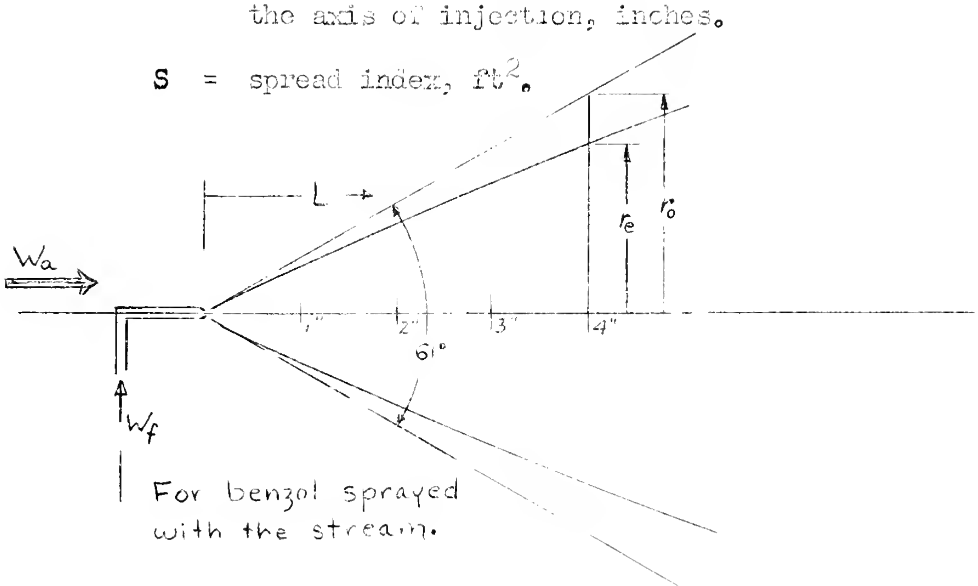
measured to obtain values of r_o. A spread index, S, was then calculated for each station from the relation:

$$S = \left| \frac{r_o^2 - r_e^2}{144} \right|$$

where r_o - radial distance from the projected cone edge to the axis of injection, inches

r_e = radial distance from apparent spray edge to the axis of injection, inches.

S = spread index, ft^2.



For benzol sprayed with the stream.

The examination of many photographs gave a spray index but great difficulty was experienced in attempting to ascertain exactly where the spray edge was. This difficulty prevented reliable detections of difference of the spread index between test conditions. The apparent spray edge measurements were therefore averaged out for all test conditions involving changes in temperature so as to obtain a representative index. Fig. 15 shows the resulting index curve for benzene sprayed at 100 psi pressure into air traveling at 80 fps with a static pressure of 27 in. Hg. abs. between the temperatures 60° F to 270° F. Index curves calculated by the methods of Ref. 9 for iso-octane sprayed contrastream under the same conditions are included, although true comparisons are

not possible due to the difference in the injectors and the methods of injection. A true criterion of the validness of the "S" index would have been an actual probing of the spray.

Having the focus of the camera at the vertical plane passing through the spray axis resulted in some excellent pictures of the drops at the spray edges, but the near and far sides of the spray were not in focus. Consequently, examinations of the spray drop sizes and apparent distributions were confined to the spray edge areas.

The scale of the photographs was determined as accurately as possible based upon the focus being at the spray center plane, however the exact sizes of individual drops were not attainable since it could not be certain that their drop images were also in this plane.

The effects noted due to various test parameters are as follows:

(1) Fuel Pressure. The fuel pressure was varied from 75 to 150 psi. An increase in the pressure gave an increase in spray density due to the increase of fuel injected, and gave a decrease in average drop sizes. The velocity of the fuel drops at the point of injection are of the same order as the air stream velocity, resulting in little or no effect attributable to droplet acceleration or deceleration. The increase in pressure tended to greatly reduce the number of random drops appearing outside of the general spray region, due possibly to the fact that the increased fuel velocity has moved

the area of comparison further downstream.

(2) Velocity. The velocity was varied from zero to 80 fps at room temperature in an effort to determine its effect upon the spray spreading index. The increase in air velocity appears to give a less dense spray, but contributes to the appearance of a ragged spray edge and random drops outside of the spray region. This is due to increased turbulence levels and an increase in forces on the spray tending to break it up. No conclusions were drawn as to the effect on the drop sizes.

(3) Temperature. The temperature was varied from 60° F to 300° F at a constant fuel pressure, and air velocity and pressure. An increase in temperature gave a less dense appearing spray, but the average drop size appeared to increase. This is due to the more rapid vaporization of the smaller droplets and their early disappearance. The ligament or sheet leaving the injector appears more dense and somewhat longer at the lower temperatures.

The low temperature photographs have a "Milky-Way" appearance due to the amount of small drops still present with the larger drops.

(4) Static Pressure. The static pressure was maintained at 27 in. Hg. abs. for all tests, and its effect was not investigated.

The possibility of studying the effects of typical fuel-air

ratios on the spray evaporation process was eliminated because of the air flow requirements for the electrical heaters. It was not possible to isolate the air flow rates from the other parameters involved and negated any possibility for a study of its effects. Typical fuel-air ratios used were .012 to .025, which is considerably less than stoichiometric.

Enlargements of the spray photographs to a scale of 5:1 enabled some measurements of drops to obtain an estimate of their order of size. Measureable drop diameters varied from .002 to .020 inches (50 to 500 microns). Drops larger in size were to be easily found but their phantomlike appearance made it very likely that their size was distorted due to being out of focus.

The experimental apparatus was quite limiting in that the fuel spray impinged upon the walls about four and one-half inches downstream of the injector and prevented any photographic examination of the spray drops further downstream where evaporation was more nearly complete. It is recommended that an injector giving a spray cone with a thirty degree included angle be used for any future tests.

The results of this investigation have shown the feasibility of the use of photographic methods for the investigation of fuel sprays in the wind tunnel. Aside from the difficulties connected with the focusing and the establishing of correct scale for drop size measurements, excellent photographs of the spray are possible. The usefulness of the proposed spread index obtained from photographs is hampered by the difficulties encountered in correctly ascertaining the spray boundaries and must be verified by further tests.

CONCLUSIONS AND RECOMMENDATIONS

The test apparatus usefulness is limited by the following:

(1) Unsatisfactory temperature and velocity profiles.

(2) Impingement of the fuel spray upon the walls a short distance after injection.

(3) Fuel-air ratios attainable are considerably less than stoichiometric.

(4) A very shallow photographic depth of field.

The use of photographic methods for the investigation of fuel sprays is feasible and only limited by the capabilities of the camera and apparatus used. A spread index is obtainable but of doubtful value until verified by further tests.

The effects of some of the various parameters upon the fuel drop sizes and distribution pattern are:

(1) Increasing fuel pressure increases the spray density and decreases the average drop sizes. The effects of varying fuel pressure are greater than the other parameters.

(2) Increasing air velocity decreases the spray density at the spray boundaries and increases the turbulence.

(3) Increasing the air temperature decreases the spray boundary density and increases the average drop size by evaporating the smaller drops immediately after injection.

(4) Measurable drop diameters varied from 50 to 500 microns.

It is recommended that:

(1) The fuel injector be replaced by another capable of giving greater downstream travel of the spray before impingement on the test section walls.

(2) The tunnel settling chamber be insulated from the metal mounting stands.

(3) Experimentation with baffles and screens be made to find a method of correcting the temperature and velocity profiles.

(4) Further tests by both photographs and spray probing be conducted to establish a true spread index.

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SYMBOLS AND NOTATION

A	Cross section area of test section, ft^2
D	Diameter of fuel injector orifice, in.
H	Static pressure in test section, in. Hg. abs.
L	Distance downstream of injector, inches.
M	Spread Index, ft^2, from Ref. 9.
P	Pressure, p.s.f.
R	Gas constant, 53,35 ft/°F.
S	Spread Index, ft^2
T	Temperature, °R.
V	Velocity, fps.
W	Flow-rate, lb/sec.
GPH	Gallons per hour
e	Exponential.
f	Local fuel-air ratio.
g	Gravity, ft/sec^2
h	Dynamic pressure, inches of alcohol.
p	Pressure, psi.
q	Dynamic pressure, psf.
r	Radial distance from a survey point to axis of injection, ft.
w	Density, lb/ft^3.
ρ	Density, $slugs/ft^3$.

SAMPLE CALCULATIONS

Velocity

Specific gravity of alcohol = .811

1 in. Hg. = 70.7 psf.

$$q = w_{alc} \frac{h}{12} = 62.4\ (.811)\ \frac{h}{12} = 4.21h$$

but for air,

$$q = \rho \frac{V^2}{2} = \frac{PV^2}{2gRT} = \frac{70.7\ HV^2}{64.4\ (53.35)\ T} = .0206\ \frac{HV^2}{T}$$

Equating:

$$4.21\ h = .0206\ \frac{HV^2}{T}$$

Solving for V:

$$V = 14.25 \sqrt{\frac{h}{H}\ T}$$

Solving for h where V = 80 fps and H = 27 in. Hg. abs.:

$h = \frac{846}{T}$ which is useful for precalculations of dynamic pressures as a function of temperature.

Air Flow Rate

By continuity,

$$W_a = \rho\ VA = \frac{PVA}{RT} \quad \text{where} \quad A = .111\ ft^2$$

$$W_a = \frac{70.7\ H}{53.35\ T} \left[14.25 \sqrt{\frac{h}{H}\ T} \right] .111$$

Thus

$$W_a = 2.09 \sqrt{\frac{hH}{T}}$$

Fuel Flow Rate

Density of Benzol = 7.31 lb/gal at 60° F.

Observed Rotameter G.P.H. corrected to benzol G.P.H. by curve of Fig. 20.

$$W_f = \frac{\left[G.P.H.\right]_b}{3600} (7.31) = .00203\ \left[G.P.H.\right]_b$$

Example

Observed test conditions are:

$H = 27$ in. Hg. abs.

$h = 1.115$ in. alcohol

$GPH = 4.8$

$T = 760^\circ R = 300^\circ F$

Calculations are:

$$V = 14.25\sqrt{\frac{h}{H}T} = 14.25\sqrt{\frac{1.115}{27}(760)} = 79.9 \text{ fps}$$

$$W_a = 2.09\sqrt{\frac{hH}{T}} = 2.09\sqrt{\frac{1.115\ (27)}{760}} = .415 \text{ lb/sec}$$

$$[GPH]_b = 3.6 \text{ from Fig. } 20$$

$$W_f = .00203\ [GPH]_b = .00203\ (3.6) = .00731 \text{ lb/sec}$$

$$F/A = \frac{W_f}{W_a} = \frac{.00731}{.415} = .0176$$

Spread Index, M

Ref. 9 gives an emperical equation for the injection of iso-octane, contrastream under the following conditions:

Air temperature 80 - 390° F

Air velocities 100 - 350 fps

Air static pressures 18 - 35 in. Hg. abs.

Axial distances from fuel injector 5 - 18 inches

Fuel-injection pressure 25 - 85 psi.

Fuel-injector orifice diameters 0.024 - 0.041 inches

The equation is:

$$M = 0.0598\ \Phi + .00042$$

where

$$\Phi = \frac{\left(\frac{T_a}{1000}\right)^{.67}(L)^{.76}(P_f)^{.49}(D)^{.79}}{\left(\frac{V_a}{100}\right)^{.85}(H)^{.57}} \quad \ldots\ldots$$

This equation was extended to axial distances of one through four inches for the following test conditions:

P_f = 100 psi.

D = .0216 in.

V_a = 80 fps.

H = 27 in. Hg. abs.

T_a = 520° R and 730° R.

Thus

$$\Phi = .0545\,(L)^{.76} \quad \text{for } T_a = 520^\circ\ R$$

$$\Phi = .0685\,(L)^{.76} \quad \text{for } T_a = 730^\circ\ R$$

TABLE I

Test data for Photographs of Benzol sprayed into the test section. Static pressure is 27 in. Hg. abs. for all data.

Temp. Air °F	Temp. Fuel °F	h	V	GPH Benzol	P_f	W_a	F/A
300	52	1.115	80	--	--	.416	----
300	52	1.115	80	3.60	75	.418	.0175
250	52	1.190	80	3.85	85	.444	.0175
200	52	1.280	80	4.15	100	.478	.0175
100	52	1.510	80	4.90	150	.563	.0175
250	--	--	--	--	100	--	.0175
250	--	--	--	--	--	--	.0175
300	56	1.115	80	3.60	75	.416	.0175
250	56	1.190	80	3.85	90	.444	.0175
200	56	1.280	80	4.15	105	.478	.0175
100	56	1.510	80	4.90	150	.563	.0175
300	56	1.115	80	3.60	75	.416	.0175
100	56	1.510	80	4.90	110	.563	.0175
270	56	1.160	80	4.15	100	.432	.0193
200	54	1.280	80	4.15	100	.444	.0175
100	54	1.510	80	4.15	100	.563	.0148
60	54	1.630	80	4.15	100	.608	.0138
300	54	1.115	80	4.15	100	.416	.0201
56	52	0	0	3.60	75	0	----
56	52	0	0	4.15	100	0	----
56	52	0	0	4.90	150	0	----
65	52	1.615	80	4.90	150	.6	.0165
65	52	1.615	80	3.60	75	.6	.0122
65	52	1.615	80	4.15	100	.6	.0140
65	52	0	0	3.45	75	0	----
65	52	1.615	80	3.45	75	.6	.0117
65	52	0	0	5.02	150	0	----
65	52	1.615	80	5.02	150	.6	.0170
290	52	1.130	80	5.02	150	.421	.0242
310	52	1.100	80	5.02	150	.410	.0248

TABLE II

PROPERTIES OF BENZOL, TECHNICAL (BENZENE)

Chemical formula	$C_6 H_6$
Molecular weight	78.11
Hydrogen-carbon ratio	0.0835
Boiling point, °F	176.2
Density at 65° F	7.31
Specific gravity at 65° F	0.877
Heat of vaporization, Btu/lb	187.
Oxygen for combustion, lb/lb benzol	3.1
Air for combustion, lb/lb benzol	13.32
Fuel-air ratio for combustion	0.075
Lower heating value, Btu/lb	17260.
Mean specific heat (93 - 240° F) C_p	1.2
Specific heat ratio, γ, at 194° F	1.1

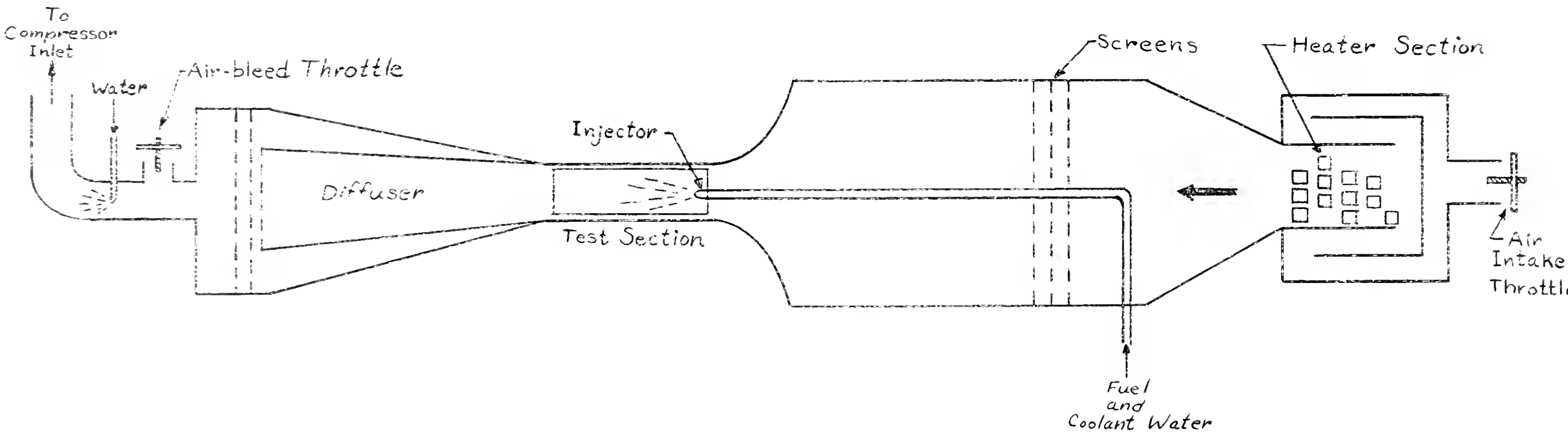

FIG. 1

WIND TUNNEL SCHEMATIC

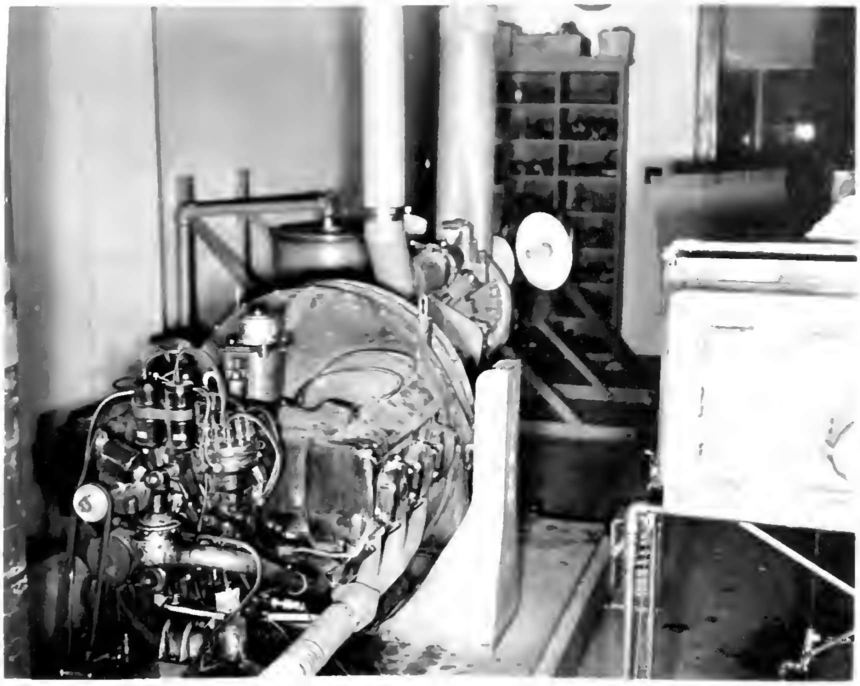

Fig. 2 The prime-mover and compressor unit.

Fig. 3 The prime-mover and compressor unit adjacent to the tunnel installation.

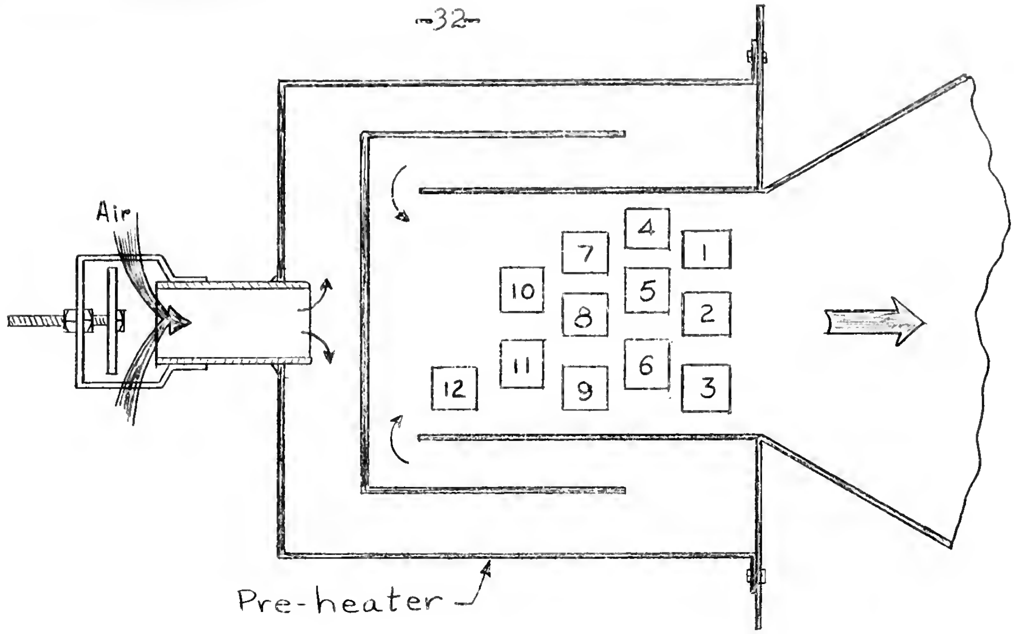

FIG. 4

HEATER INSTALLATION

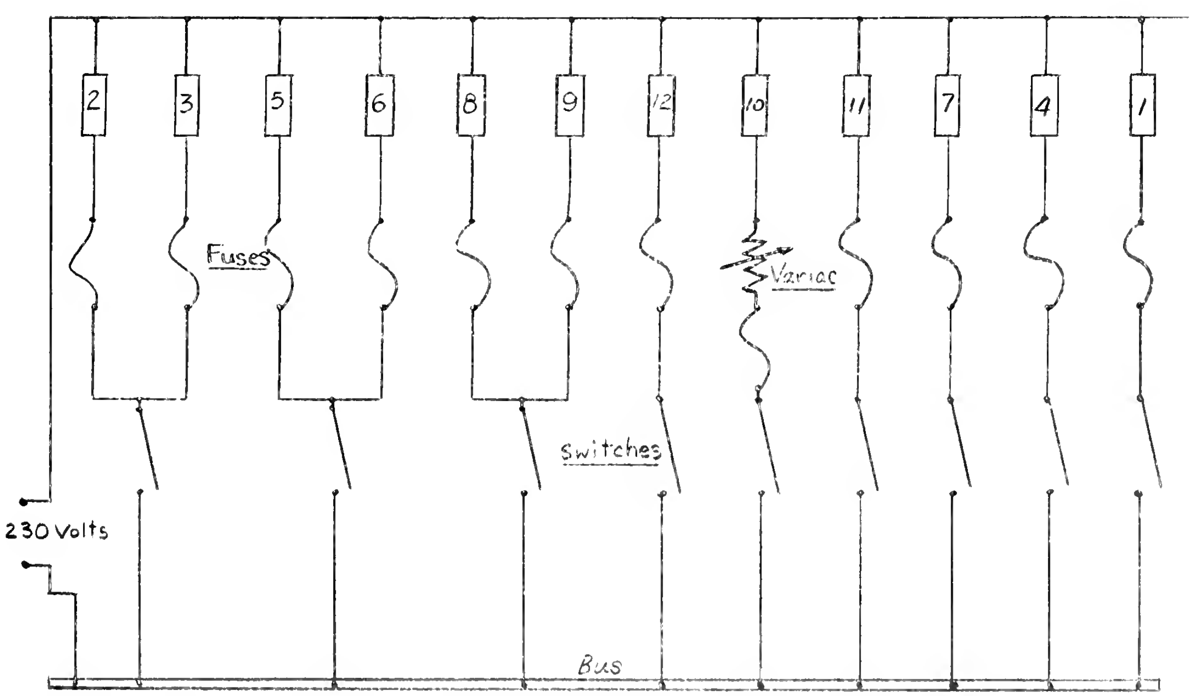

FIG. 5

HEATER WIRING DIAGRAM

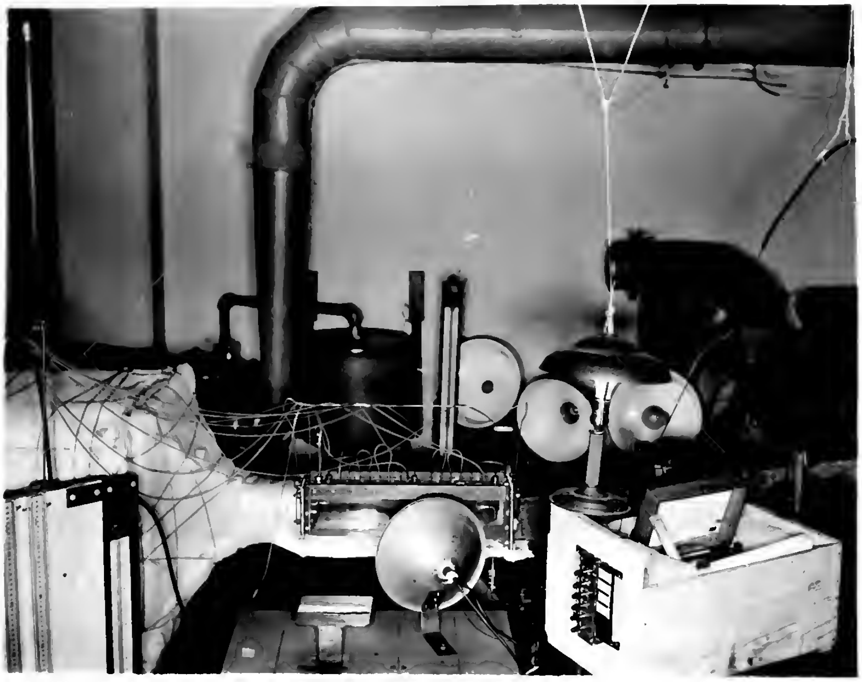

Fig.6 The test section showing the flash unit and camera mounting bracket.

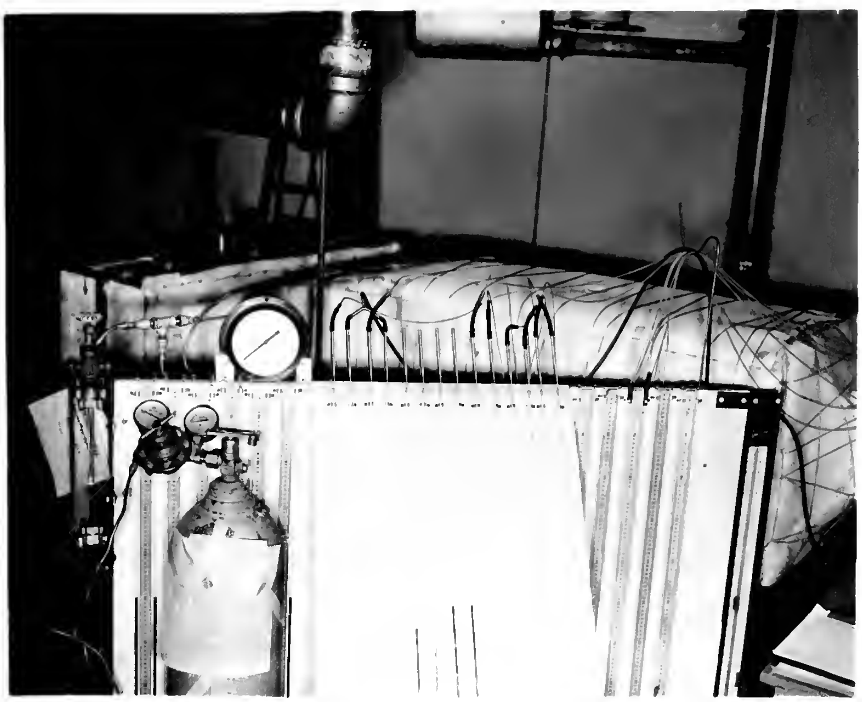

Fig.7 The fuel rotameter, pressure gage, and CO_2 system at the manometer board.

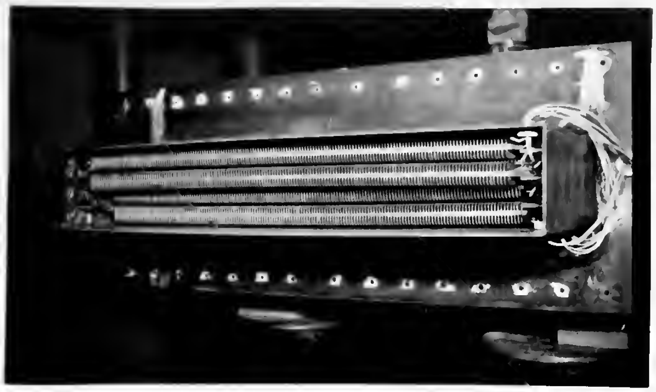

Fig.8 The pre-heater jacket removed to show the heater elements.

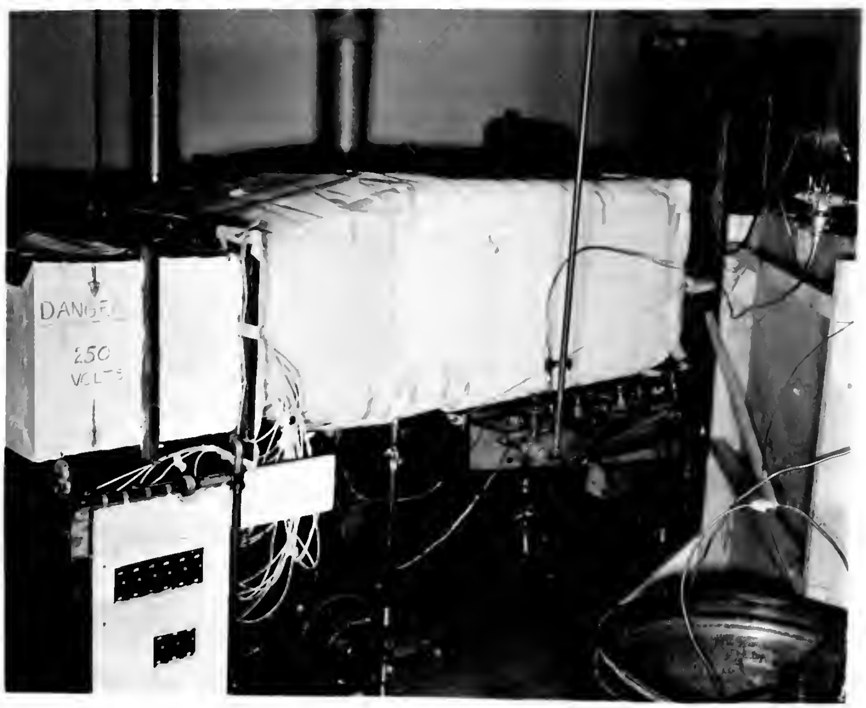

Fig.9 The heater section and settling chamber with heater switch-board, variac, and the water and fuel plumbing.

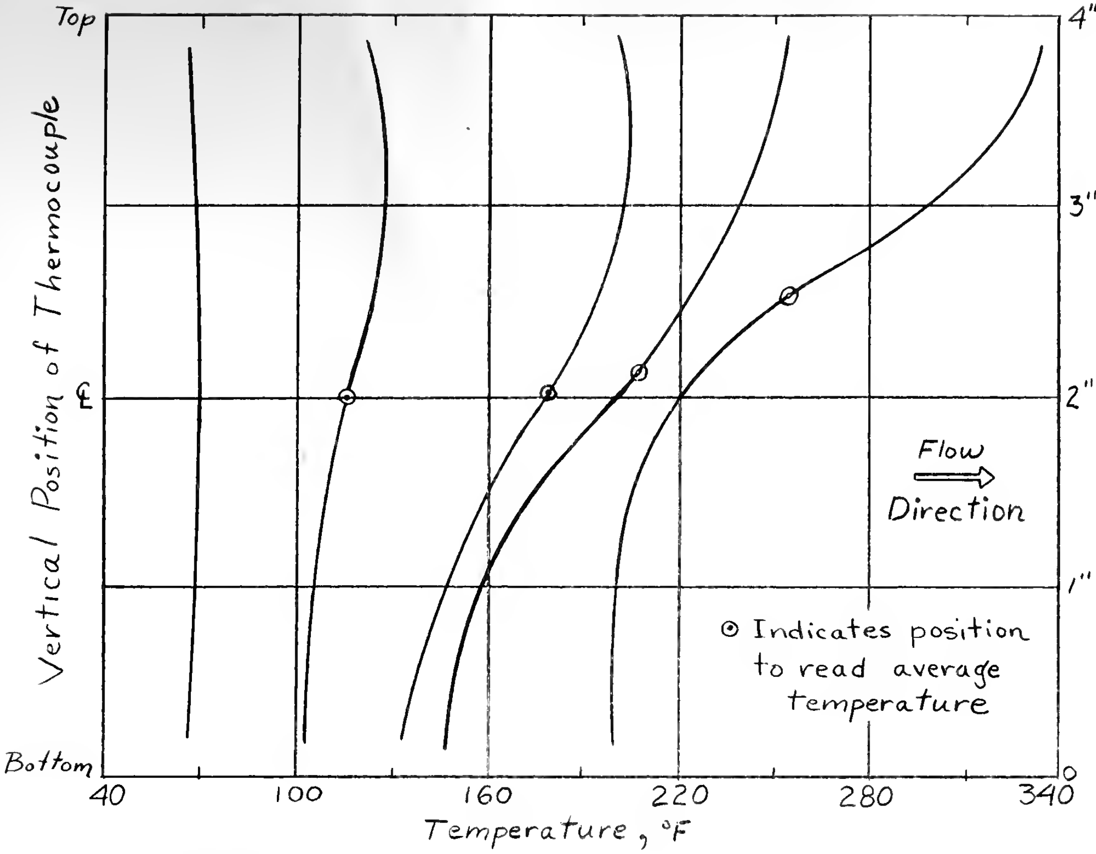

Fig. 10. Typical test section temperature profiles for various heat energy levels.
V=80fps , P_a=27 in. Hg. abs.

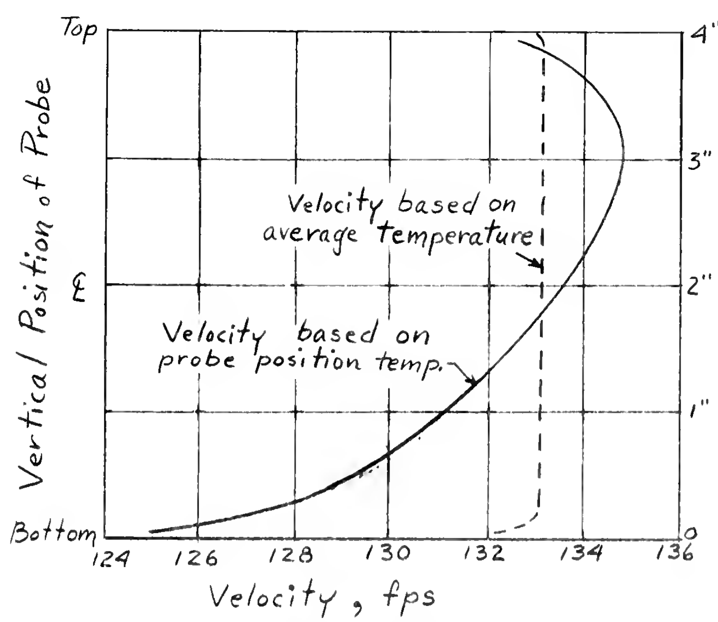

Fig. 11. Typical velocity profile.
Average test section temperature is 200° F.
P_a=27 in. Hg. abs.

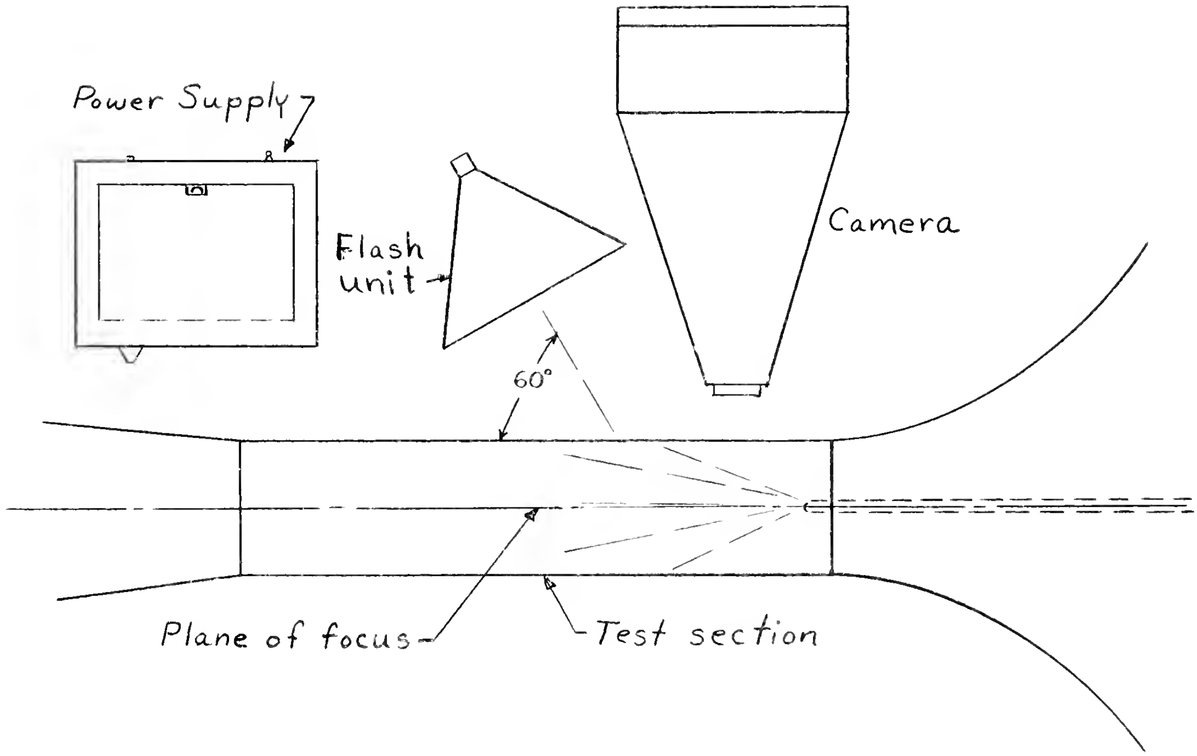

Fig.12. Plan view of the camera and flash unit arrangement about the test section.

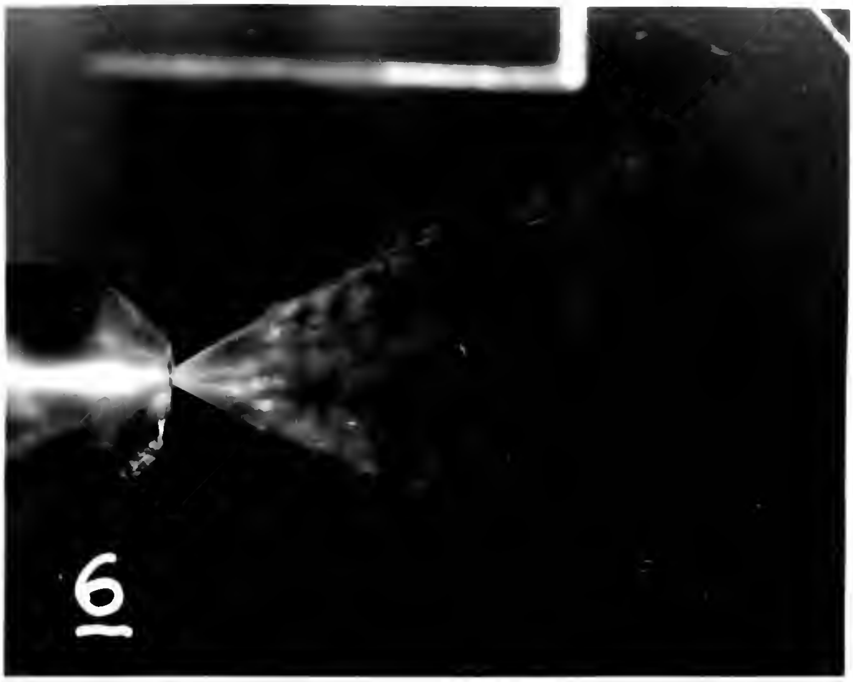

Fig.13 A close-up of the fuel spray as obtained with the STROBELUX.

Fig.14 A close-up of the fuel spray as obtained with the mercury-arc lamp.

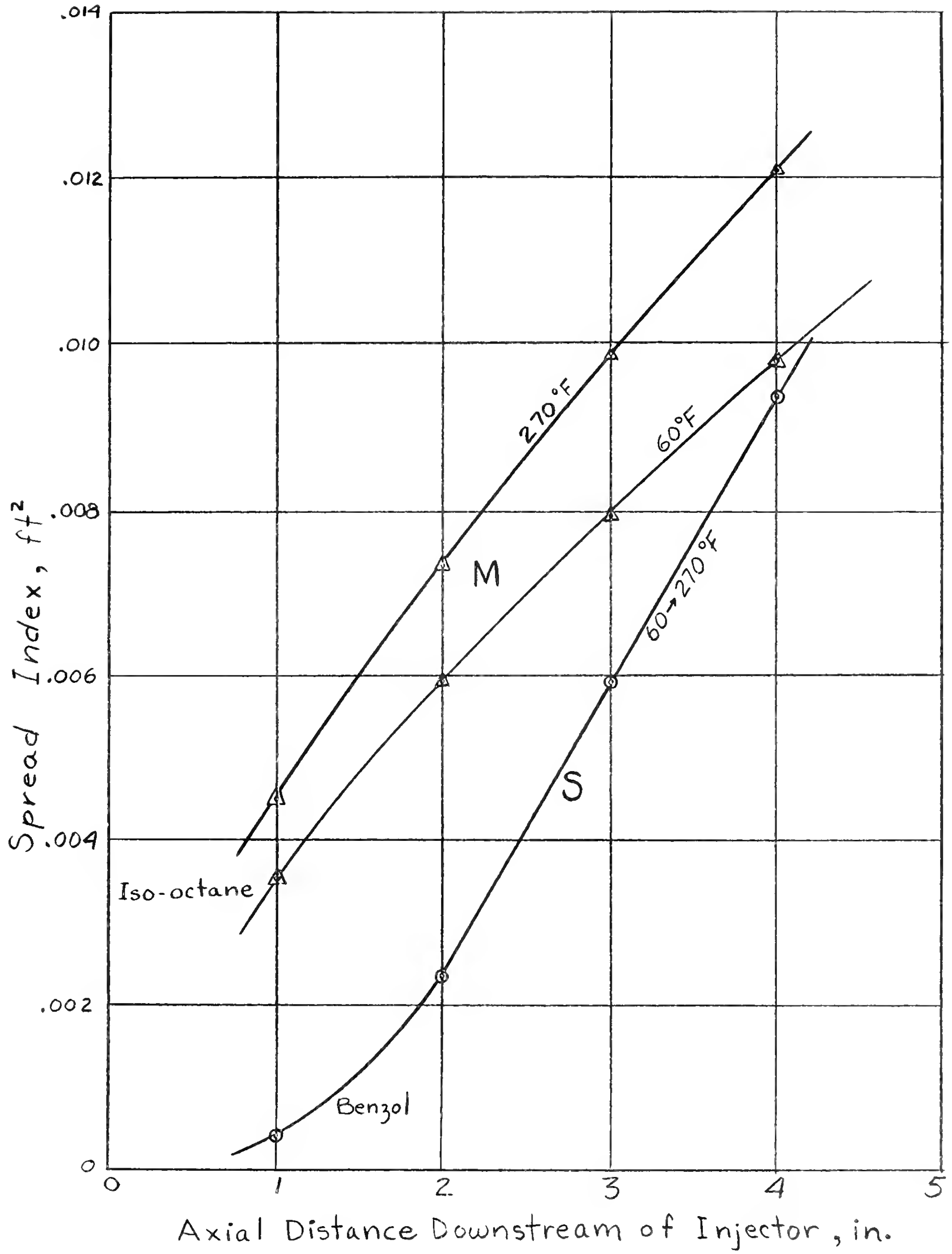

Fig.15. Spread Indexes for iso-octane sprayed contra-stream and benzol sprayed with the stream.
P_f=100psi., P_a=27in.Hg.abs., V=80fps., Injector orifice diameter of .0216 inches.

Fig.16 Benzol at 56°F and 75 psi sprayed into air at 300°F, 27 in.Hg.abs., and 80 fps. F/A is .0175

Fig.17 Benzol at 52°F and 75 psi sprayed into air at 65°F, 27 in.Hg.abs., and 80 fps. F/A is .0122

Fig.18 Benzol at 56°F and 100 psi sprayed into air at 270°F, 27 in.Hg.abs., and 80 fps. F/A is .0193

Fig.19 Benzol at 54°F and 100 psi sprayed into air at 60°F, 27 in.Hg.abs., and 80 fps. F/A is .0138

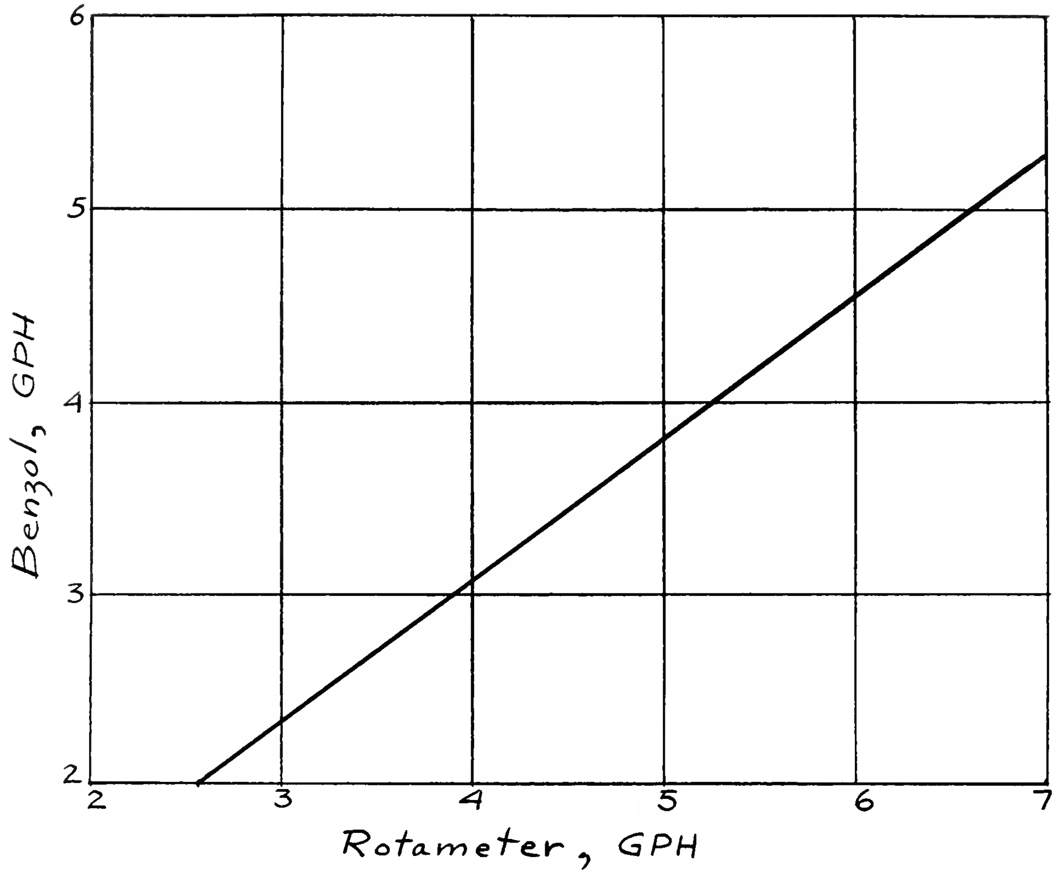

Fig. 20 Rotameter and fuel pressure calibration.

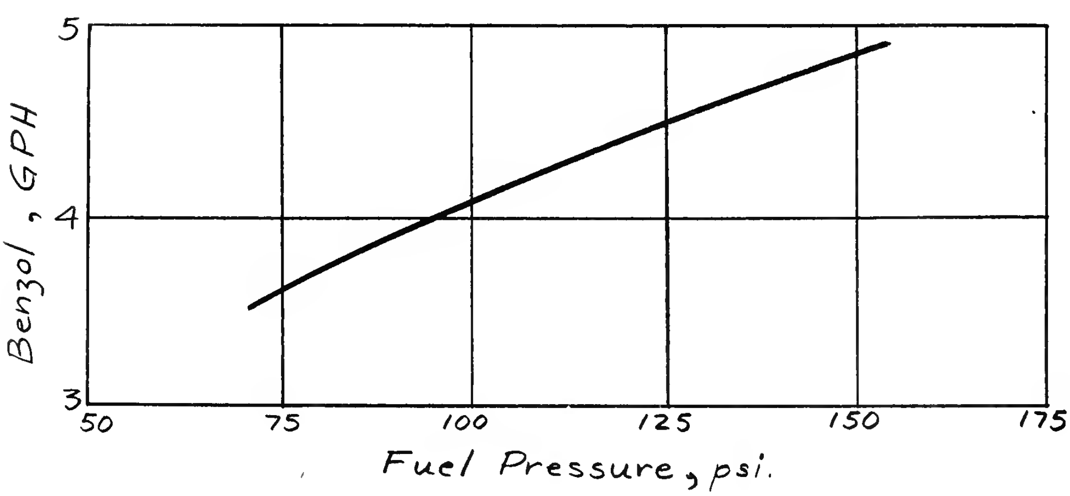

Fig. 21
Benzol spray
$T = 65^{\circ}$ F
$V = 80$ fps
$P_a = 27$ in. Hg. abs.
$P_f = 75$ psi
Scale = 5:1

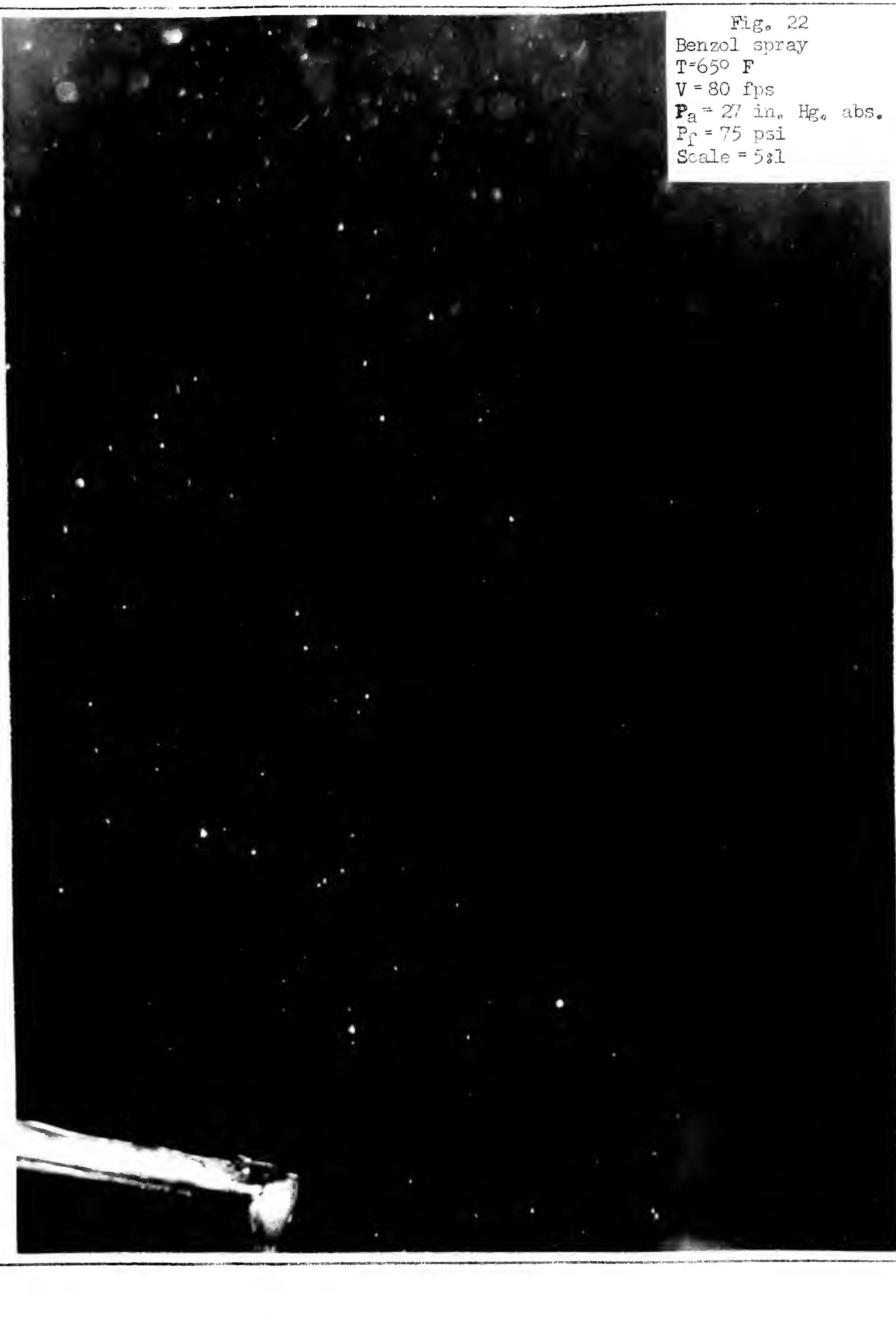

Fig. 22
Benzol spray
$T = 65^{\circ}$ F
$V = 80$ fps
$P_a = 27$ in. Hg. abs.
$P_f = 75$ psi
Scale = 5:1

Fig. 23
Benzol spray
T = 300° F
V = 80 fps
P_a = 27 in. Hg. abs.
P_f = 75 psi
Scale = 5:1

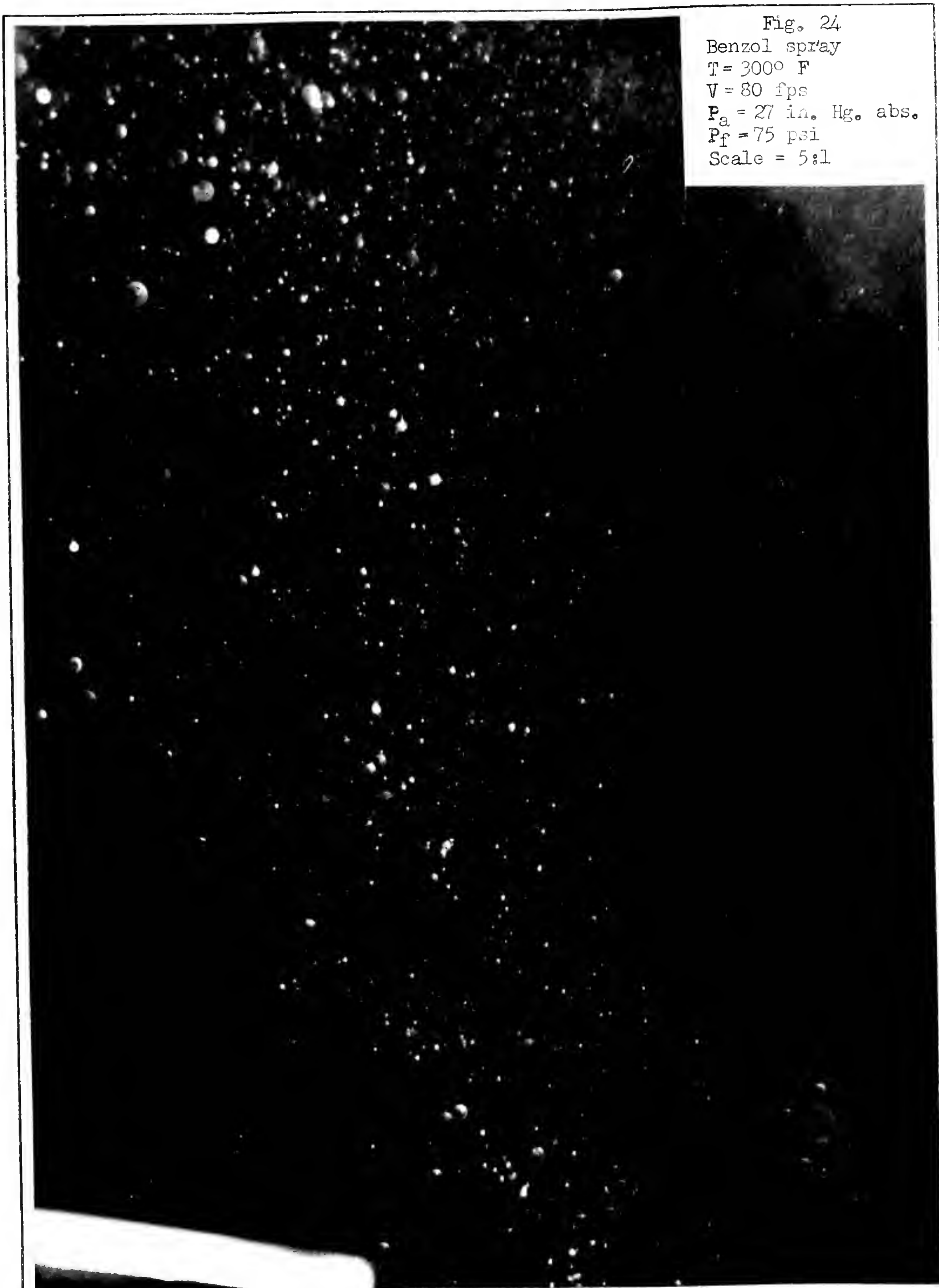

Fig. 24
Benzol spray
$T = 300^{\circ}$ F
$V = 80$ fps
$P_a = 27$ in. Hg. abs.
$P_f = 75$ psi
Scale = 5:1

Fig. 25
Benzol spray
T = 60° F
V = 80 fps
P_a = 27 in. Hg. abs.
P_f = 100 psi
Scale = 5:1

Fig. 26
Benzol spray
$T = 60^\circ$ F
$V = 80$ fps
$P_a = 27$ in. Hg. abs.
$P_f = 100$ psi
Scale = 5:1

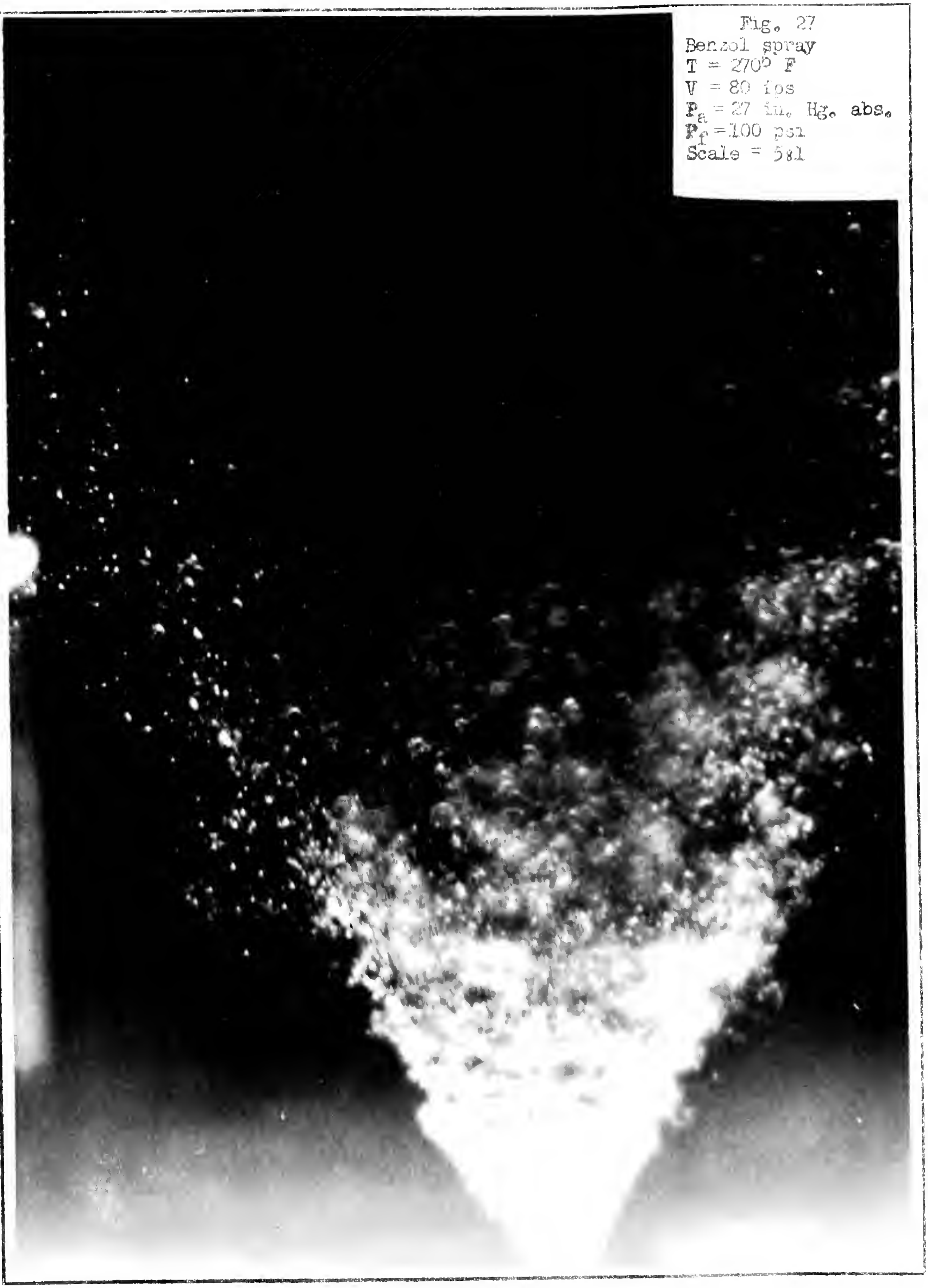

Fig. 27
Benzol spray
T = 270° F
V = 80 fps
P_a = 27 in. Hg. abs.
P_f = 100 psi
Scale = 5:1

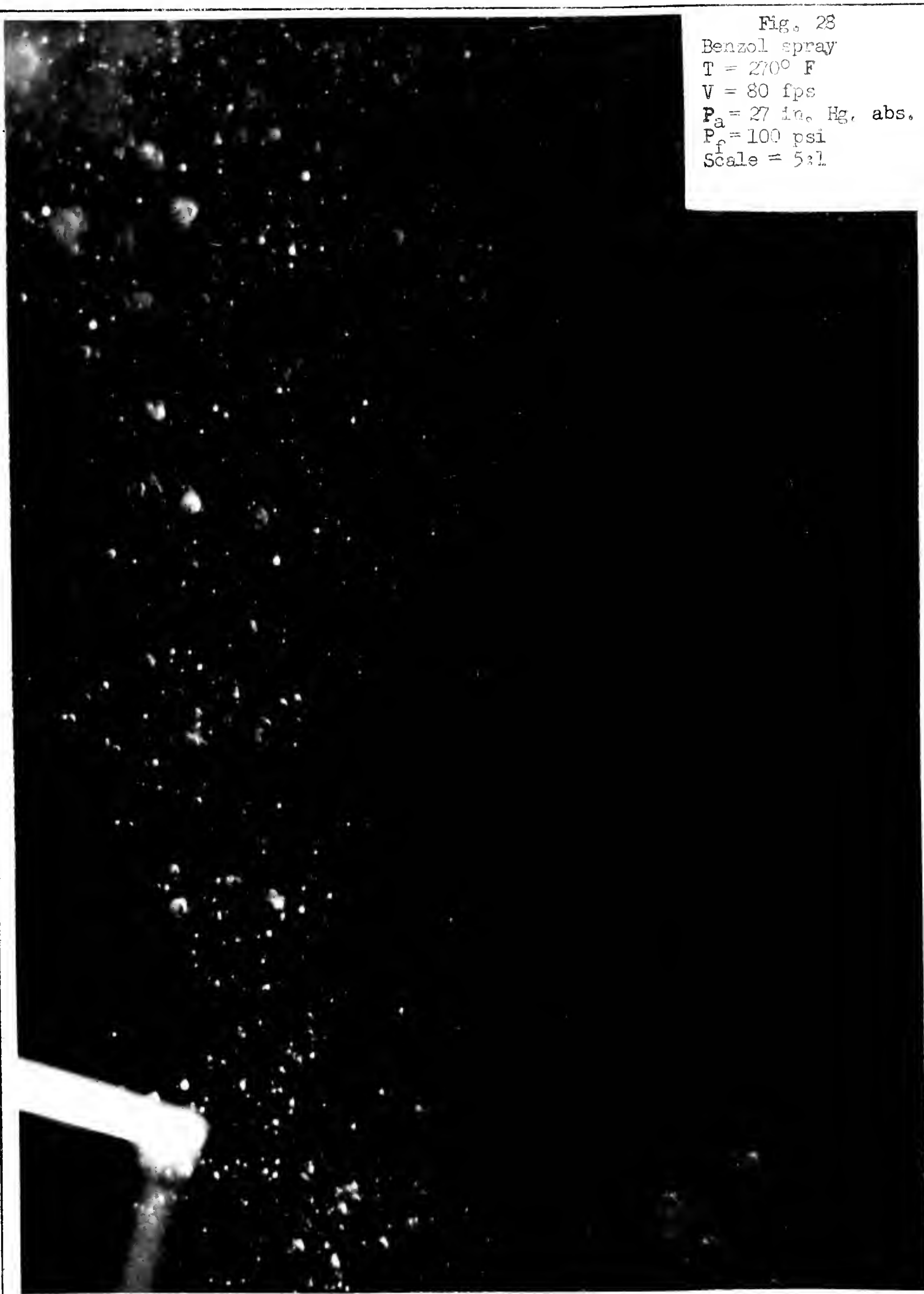

Fig. 28
Benzol spray
$T = 270^{\circ}$ F
$V = 80$ fps
$P_a = 27$ in. Hg. abs.
$P_f = 100$ psi
Scale = 5:1

Thesis 33164
S414 Seligmiller
An investigation of the distribution pattern of fuel sprays under conditions of interest in jet engines.